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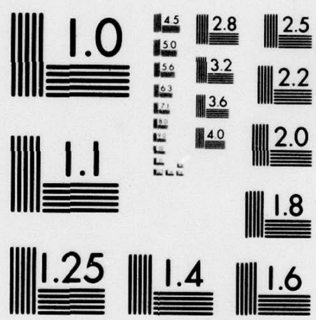

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CONT

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LABORATORY TESTS FOR DYNAMIC ICE-STRUCTURE INTERACTION

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1. INTRODUCTION

The case of dynamic ice structure interaction appears when either the elastic deformations of the structure or ice, or both, are affecting the ice failure process. Typically, this state occurs with slender flexible structures as bottom-founded piers, lighthouses or monopods while moving ice sheet is crushing against them. The physical reasoning lies on the fact that the resistance of ice is dependent on the loading rate which on its behalf depends on the initial moving velocity of the ice and on the elastic deformation rate of the structure or the ice at the contact area.

The ice force fluctuations and hence dynamic stresses in structures will be considerably greater than in the case where there is no dynamic interaction. There are two theories about the origin of these periodically repeating force fluctuations, which in the worst case may resonate with the natural modes of the structure. The first theory explains the oscillating ice force to be a property of ice alone, the characteristic of ice (Peyton, 1966) or the result of ice to break into floes of certain size in crushing (Neill 1976). The second theory (Maattanen, 1978) starts from the physical properties of ice-strength vs. loading rate and takes into account also the dynamic behavior at the structure.

Measurements for the dynamic ice-structure interaction have been rather limited. In most cases the only objective has been to measure the maximum ice force values. Reported results this far have indicated the existence of continuously repeating ice forces with frequencies from 0.5 to 15 Hz during in-situ measurements. If dynamic interaction is not occuring the ice force histogram is random with smaller fluctuations. Only one reported laboratory test for dynamic ice forces exists (Peyton, 1966).

The drawback of field tests is that the control of the most important parameters ice strength, thickness and velocity is poor and chances to repeat the test in identical conditions is minimal. In laboratory simulations the difficulties are mainly in the correct scaling. However, the superior control of main parameters, better measurement accuracy and chances for comparative tests more than outbalance the scaling difficulty.

The author of this paper expresses his gratitude to two facilities: to the University of Oulu, Finland, from which he had sabbatical and to the U.S. Army Cold Regions Research and Engineering Laboratory at which, during this time, he was able to conduct tests for the dynamic ice-structure interaction in the new Ice Engineering Facility test basin. The main objective of these tests was to measure the effects of both the ice and structure parameters to the rise of ice-induced structural vibrations, the ice force dependence on loading rate, amount of ice-induced positive and negative damping, and the concept of dynamically stable structures. The following paper includes the description of test arrangements, instrumentation, data processing and of results thus far.

2. TEST SET-UP

The CRREL Ice Engineering Facility test basin is 33.5 m long, 9.15 m wide and 2.44 m deep. The simulation of the ice moving against a structure is arranged so that the test structure is attached to the bottom of the test basin near the far end and the ice sheet is then pulled against it, Figure 1. At the rear end of the basin there is a slope and the moving ice sheet rises along it and falls down over the edge to the melt tank.

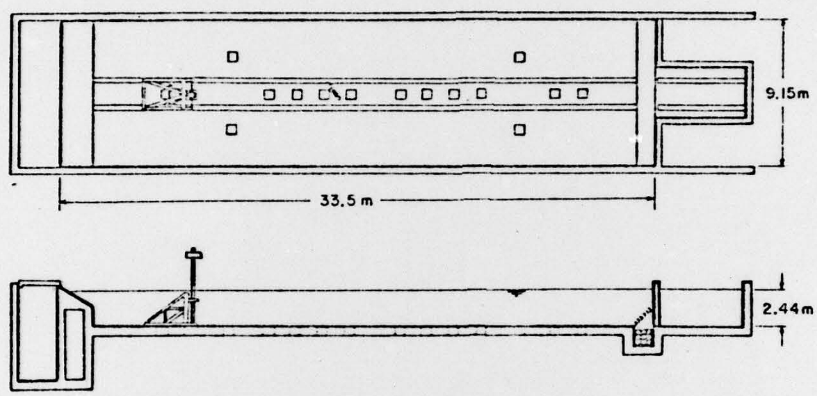

Figure 1. Test Basin

The ice crystal size is controlled by seeding with steam at 15 to 20°C whereafter the ice growth occurred usually at 25°C. Before tests the temperature is adjusted to predetermined level. With saline ice the temperature is raised in such a pace to get also correct E/σ scaling (Schwartz, 1975). The walls of the test basin are heated at the water line to keep ice from adfreezing to walls and to guarantee free ice movement during the test. Open area at the walls is, depending on temperatures and the length of warm up period, from 1 to 10 mm. Thus, lateral confinement is minimal and the crushing situation is more like that of a finite floe.

After the whole ice sheet is pulled against the structure and to the melt tank, a new freezing period can be started. Meanwhile, the heat extracted from making new ice is used to melt the previous ice in the melt tank. As a curiosity it should be mentioned that the whole heating of the building, including offices, is taken from the cooling of test areas. Capacity of the system is to make an ice sheet thicker than 25 mm in a day. So one test each day can be accomplished.

The ice thickness variation along the length of test basin has been less than ± 3% with fresh water ice and less than ± 10% with saline ice. The main reason for unevenness is frost buildup on the ice surface. Ice upper surface temperature variations have been usually less than ± 0.2°C. Due to difficulties in measuring ice-sheet strength and modulus of elasticity, most tests are planned to be comparative: the test basin length is divided into two or three parts and a test with only one parameter changed is made subsequently to each of them. As the time required to carry this through is less than one hour, ice properties can be regarded to be the same for each configuration. In later tests seismic techniques have been utilized to measure the velocity of sound and the modulus of elasticity of ice. The crushing strength is obtained in any case as the primary data.

The ice movement is achieved using a 7 kW DC motor with thyristor drive to turn reduction gear and winches which pull semi-circular ice boom through steel wire ropes. A semi-circular ice boom was designed to make it lightweight and easy to handle. In addition, the circular boom exerts constant pressure to the ice sheet. The drive is capable of ice forces up to 35 kN and velocities from 0 to 0.20 m/s. In a typical run velocity is first increased from zero with constant acceleration to maximum and then back to zero similarily so that the total cycle lasts about 200 seconds. This gives a velocity sweep to excite all possible natural modes. As the natural frequencies are from 2.5 to 130 Hz, the velocity is from their point of view pseudo-constant.

The major drawback of the drive is the flexibility of steel wire ropes. This causes a jerking ice movement with wire ropes tightening and then suddenly slackening as the ice fails against the structure. The dynamic interaction is not between ice and structure as intended but between ice and drive. With higher velocities the interaction between steel wire ropes disappears but then the loading rate from the test pile interaction point of view is already far in the brittle region. Installing hydrodynamic drag dampers in conjunction to the ice boom stabilizes a little the jerking movement but does not remove it totally in the low and most interesting velocity range. The cure for this problem will come together with the permanent test carrier bridge which is moving above the test basin using track and pinion traction. The test carrier can then be used to move ice smoothly on the whole velocity range.

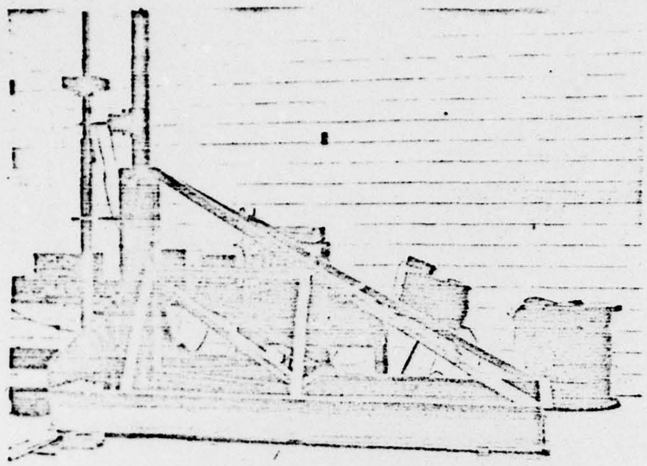

Figure 2. Test Pile and Supporting Structure

The test pile, Figure 2, is supported by a rigid frame that is bolted to the bottom of the test basin. The dynamic properties of test piles can be varied largely to simulate different actual structures. Its stiffness is varied by installing the upper supporting clamp in different positions, its natural frequencies and modes can be varied by varying the stiffness or by installing weights to the superstructure. Also external damping elements can be installed. The range of spring constants for ice forces is from 0.54 to 8.1 MN/m and the first natural frequency from 2.0 to 43 Hz and the second from 7.0 to 80 Hz. The waterline diameters of the pile have been 63.5, 101.6 and 177.8 mm. Also, different shapes other than circular can be easily installed, including inclined wedges.

Instrumentation in the test pile includes strain gages at the support clamp for the reaction of ice force and at the lower part of superstructure for the elimination of superstructure inertial effects. The test pile transducers were calibrated using both static and dynamic known loadings. Accelerometers at the superstructure are used to measure the dynamic response. One accelerometer is installed on the ice to measure ice jerking.

Both analogical and digital recording is used. All the signals are recorded to instrumentation tape recorded and simultaneously strain gage signals and drive RPM are digitized using a data-logger. Digitized signals are stored on floppy disks. All the instrumentation is controlled by calculator during measurement. The scheme of data recording and processing is shown in Figure 3.

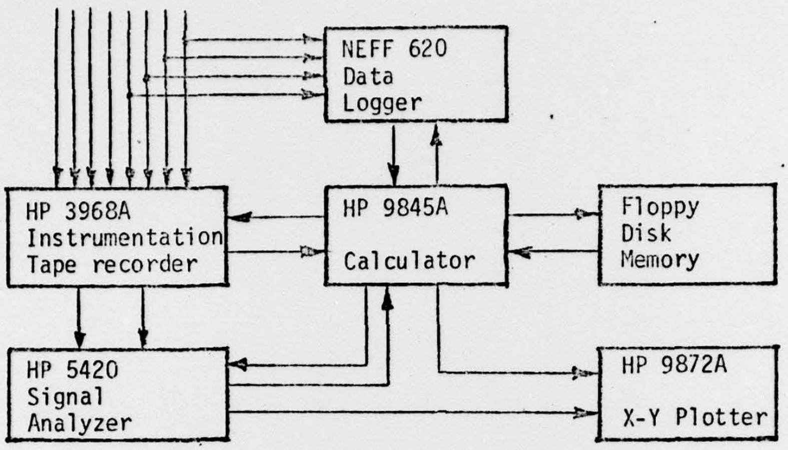

Figure 3. Signal Recording and Processing

In a typical test run, first the initial state and a shunt calibration of each data channel are recorded both analogically and digitally. Then the calculator monitors either the drive RPM or the ice force and whenever a predetermined level is exceeded, switches on the tape recorder, signal analyzer, and starts data logging. At the end of the test final state readings are recorded.

3. ANALYZING PROCEDURES

The main interest in the data processing is the real ice force between the ice and the test pile. As the direct force measurement is not possible corrections for the dynamic response of the structure or load cell has to be calculated. It should be noted that all published dynamic ice force records thus far are not pure ice force records but include also the response effects of the structure and/ or load cell.

In digital signal processing the dynamic inertia effects of the superstructure are eliminated using the moment and shear force values from strain gage measurements just above the waterline. Although the inertial effects of the pile below waterline is not taken into account, dynamic calibrations proved that it is possible to obtain the coefficient of correlation from 0.92 to 0.99 between the calculated ice force and the known excitation force with a frequency range up to 65 Hz. In the case of resonances the coefficient of correlation worsened to 0.23 due to phase shifts.

Outputs from the calculator are: corrected ice force histogram, ice force vs. loading rate plot, maximum and minimum values of the ice forces, its mean and standard deviations.

In analogical signal processing in reality also digital the correction to ice force is done using transfer function between ice force and the pile support gage. The transfer functions were first measured using a shaker excitation with a frequency sweep from 5 to 150 Hz but later a simpler impact hammer method was adopted. In the latter an impact through a load cell is given at the point of ice action. The impact gives an even energy distribution from 0 to 300 Hz and it can be easily accomplished at the beginning of each test. The signal analyzer then calculates the transfer function from the signals of impactor load cell and the ice force reaction support gage.

The real ice force can then be solved as follows. The measured signal f(t) can be expanded into Fourier integral - extension of Fourier series expansion - and in the case of forced vibration it will be

$$f(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} H(\omega)S_F(\omega)e^{i\omega t}d\omega \tag{1}$$

where $H(\omega)$ is the transfer function and $S_F(\omega)$ the linear spectrum of the forcing function. The Fourier transform for Equation 1 gives

$$H(\omega)S_F(\omega) = \int_{-\infty}^{\infty} f(t)e^{-i\omega t}dt = S_f(\omega) \tag{2}$$

which is the linear spectrum of the measured signal f(t). From this $S_F(\omega)$ can be solved and then the inverse Fourier transform gives the requested real ice force

$$F(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{S_f(\omega)}{H(\omega)} e^{i\omega t}d\omega \tag{3}$$

Although the above equations look complicated the signal analyzer solves them quickly using numerical fast Fourier transform algorithms. Same calculations could be carried out similarly in any computer for digitized data. As this transfer function approach is the only way to obtain the real ice force, it is recommended that it is used also in field measurements.

In addition to the real ice force plots, the signal analyzer is used for other time and frequency domain analysis: power spectras, cross spectras, phase information, and damping. The raw data that has been processed can then be stored in refined digital form to tape cassettes in the signal analyzer.

Another way for signal analyzing is comparisons to the predictions of mathematical models. The FEM model of the test pile can be calibrated to give stiffness and the first natural frequency exactly. For dynamic model the dampings measured in calibrations can be utilized. Then by comparing the measured response to the predicted and the existence of vibrations to the predicted stability criterions, the amount of ice-induced positive or negative damping can be figured out.

4. SCALING LAWS

The scaling down of a real structure for model tests can be done geometrically. Exact geometric scaling is not necessary: it is required that the dynamic behavior - natural modes and frequencies - follows that of the full scale structure. In the case of ice-structure interaction, it is enough to scale only those natural modes that contribute significantly to the deformations at the ice action point. In field observed range for frequencies is up to 15 Hz.

The discretized dynamic equations of motion of the structure are:

$$[k]\{\delta\} + [d]\{\dot{\delta}\} + [m]\{\ddot{\delta}\} = \{F(t)\} \tag{4}$$

where [k], [d] and [m] are the stiffness, damping and mass matrices of the structure, $\{\delta\}$ nodal displacement vector, $\{\dot{\delta}\}$ and $\{\ddot{\delta}\}$ velocity and acceleration vector respectively, and $\{F(t)\}$ the excitation ice force. If geometric scaling factor n and ice strength factor p are applied and the material of the model and the original structure kept the same, then for model with index m the following scaling terms are derived starting from the beam bending stiffness term $k \approx EI/L^3$

$$\begin{aligned} F_m &= n^2 p F & \quad t_m &= nt \\ k_m &= nk & \quad \delta_m &= np\delta \\ d_m &= n^2 d & \quad \dot{\delta}_m &= p\dot{\delta} \\ m_m &= n^3 m & \quad \ddot{\delta}_m &= n^{-1} p\ddot{\delta} \\ & & \quad \omega_m &= n^{-1}\omega \end{aligned} \tag{5}$$

Similarly, comparing term by term in the differential equation, the non-diagonal terms for [k], [d], and [m] (not given in Equation 5), can be derived.

The in-plane vibrations of the ice sheet are governed by the differential equations:

$$\frac{\partial^2 u}{\partial x^2} + \frac{1-\nu}{2}\frac{\partial^2 u}{\partial y^2} + \frac{1+\nu}{2}\frac{\partial^2 v}{\partial x \partial y} = \frac{\rho(1-\nu^2)}{E}\frac{\partial^2 u}{\partial t^2}$$

$$\frac{\partial^2 v}{\partial y^2} + \frac{1-\nu}{2}\frac{\partial^2 v}{\partial x^2} + \frac{1+\nu}{2}\frac{\partial^2 u}{\partial x \partial y} = \frac{\rho(1-\nu^2)}{E}\frac{\partial^2 v}{\partial t^2} \qquad (6)$$

where u and v are the displacements in the x and y directions, ν the Poisson's ratio, E modulus of elasticity and ρ the density of ice. The coefficient on the right hand side $\rho(1-\nu^2)/E$ is equal to $1/c^2$ in which c is the plate compressional wave velocity. Thus the measuring of c by seismic tests is recommended. As can be seen, the geometric and time scaling similarity as in Equation 5 guarantee the similitude provided the ice properties are the same. The ice grain size scaling geometrically is an essential requirement.

If ice strength is scaled by p in Equation 5, the displacements of the structure are scaled np times. Then also ice displacements u and v shall be np times from that of full scale. The similitude then requires the modulus of elasticity to remain the same. This is usually impossible, since in practice if ice strength is scaled down, the modulus of elasticity will change much faster. This suggests that the geometric scaling n only should be applied with ice scaling p = 1.

In dynamic ice-structure interaction, the appearing ice force depends on the relative velocities between the structure and the ice. While p = 1, this important parameter would be unchanged in the scaling, e.g. with n = 1:10 and p = 1 the displacements of the model and ice will be one tenth, velocities the same and accelerations ten times greater than with the full scale. However, the situation is different for the stress rate $\dot{\sigma}$. For ice moving against a circular pile with velocity v it is (Blenkarn, 1970)

$$\dot{\sigma} = \frac{4\sigma_c v}{\pi a} \qquad (7)$$

where σ_c = ice crushing strength and a = the half of the pile diameter. To have stress rate identical for both the model and full scale requires $p^2/n = 1$. If p = 1 the similitude cannot be achieved. On the contrary if $p \neq 1$ the ice in-plane vibration similitude cannot be obtained. Thus, in either case a compromise has to be made. Thus far it is unknown how the ice strength versus stress rate changes from full scale to model.

One [illegible] in the scaling is the floe size. In the test basin only finite size ice field is possible. As the edges are free due to wall heating, the situation is that of a floe acting against the pile. Lateral confinement does not exist, but if no longitudinal cracks appear, the affect of boundary conditions will be insignificant to crushing. The corresponding floe size in full scale would be typically greater than 100 m by 300 m.

5. SOME RESULTS

A typical ice force plot is presented in app. 1. At first starting with low velocity, there is interaction with the ice pulling steel wire ropes and the ice force. After 9 cm/s this interaction is no longer possible and then interaction starts with the pile. In some cases, e.g. in app. 2, while the velocity was greater than 13 cm/s the pile stabilized and the crushing occurred with an almost constant ice force. If stress rate is calculated from Equation 7, it appears that in this case minimum loading rate is with the smallest ice force and highest velocity. This is in contradiction to uniaxial tests, which suggests that either the Equation 7 is not valid or that in Equation 7 only the reference value of σ_c should be used and not the actual value for each particular loading rate.

The effect of interaction mode is paramount to the ice forces. In all cases the highest forces were recorded while the interaction with the pulling system was occurring in low speed. The reduction with higher loading rates was considerable, down to 40-70% from the maximum and as an ultimate to 10% in test 27 in app. 2. The reduction occurs both with saline and fresh water ice. Figure 4 shows the results of ice force vs. loading rate.

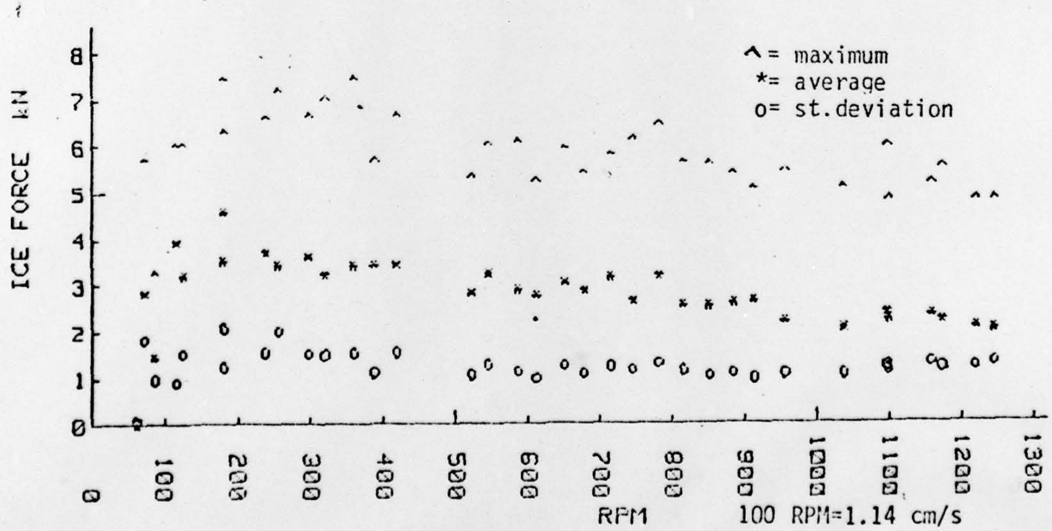

Figure 4. Ice Force vs. Loading Rate

Each individual point is the result of 3.6 second period from the curve in app. 1. As can be seen the maximum occurs with 200 rpm, 2.3 cm/s, and thereafter both the maximum, average and standard deviation are all decreasing. The reduction in the standard deviation is the least. This type of presentation is useful in design: the probability of maximum ice force to become greater than the average plus three times the standard deviation is very small. Thus an ice force of (4.6 + 3.20)kN = 10.6 kN extrapolated to full scale would be an adequate design load. As ice structure interaction is a nonlinear phenomenon and as it affects strongly the recorded ice force values, great care should be taken to observe interaction possibilities.

Although the jerking ice movement prevented the ice/test pile interaction with velocities less than 8 cm/s the interaction with steel wire ropes gives some information about ice forces against ultra flexible structures. The natural frequency of pulling systems varies from 0.5 to 2.7 Hz and if this is changed to full scale (1:10) it corresponds to a frequency range of 0.05 to 0.27 Hz. The cable tensioning and slackening is nonlinear and it cannot sustain compressive loads. Anyhow, the ice force repeats itself periodically, app. 1 & 2, as long as drive velocity is sufficiently low. It can be proved that the vibrating system ice-mass with wire ropes acting as supporting springs and excited with loading rate dependent ice crushing force is dynamically unstable. If the frequency of ice force peaks is predicted using Equation 8 (Maattanen, 1978)

$$f = \frac{kv}{F_{max}} \tag{8}$$

the results will be of correct order but a little higher than what it is in reality. This performance of Equation 8 coincides with another comparison of Equation 8 to more accurate theoretical limit cycle frequencies. Due to too many and too little known nonlinearities in the steel wire rope pulling system, no mathematical model has been developed for this case.

With increasing velocity the ice force excitation frequency, Equation 8, goes up and after a while interaction between steel wire ropes is no longer possible. As this is what happens with the model, it supports the theory that the reason for ice-induced vibrations is the result of the ice strength dependence on the loading rate rather than the result of ice tending to break into floes of certain size. Also, e.g. with 300 rpm, 3.4 cm/s, the floe size should be about 4 cm instead of from 1 to 3 mm rubble as observed in crushing. The dynamic interaction theory also neatly explains the shift from the pulling system interaction to the ice/pile interaction with increasing velocity, see app. 1 & 2, and to the stable state in app. 2.

In app. 3 there are time expansions of the ice force plot in app. 2. In the first sample the drive velocity is low but the energy stored in the cables accelerates the ice to so high a velocity that crushing occurs with same frequencies as with higher drive velocity in sample 2. The pile has natural frequencies of 43 and 103 Hz. The ice force excites the first fundamental mode slightly but most of the energy of ice force is in the 82 to 87 Hz range which is lower than the second natural frequency. With the highest drive velocity neither of these frequencies is present, the pile is stable. In 1:10 scale this situation would simulate crushing for a structure having natural frequencies of 4.3 and 10.3 Hz, pile diameter 1.0 m and ice thickness 59 cm.

The amount of data and observations, and possibilities to simulate the dynamic ice structure interaction in laboratory tests is so great that it is out of the scope of this paper. More detailed results will be published in a CRREL report after the tests with low speeds have been completed. In addition to topics briefly treated here, it will include data on: dynamic aspect ratio effect, velocity dependence of crushing to buckling mode change, corrections for measured ice forces, existence of dynamically stable structural modes, capabilities of predicting crushing force frequencies and amplitudes, ice-induced positive or negative damping.

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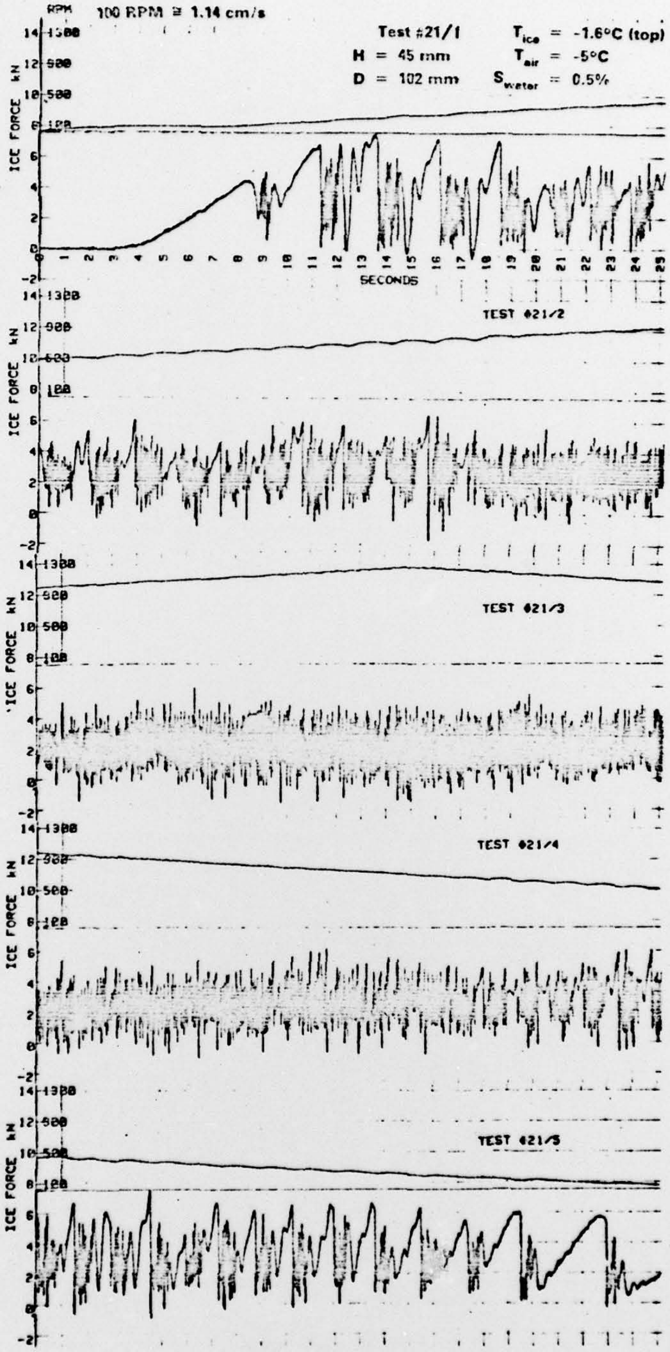
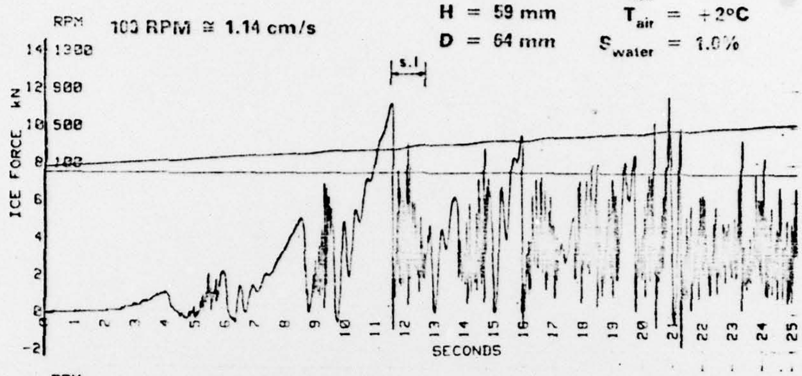
APPENDIX 1

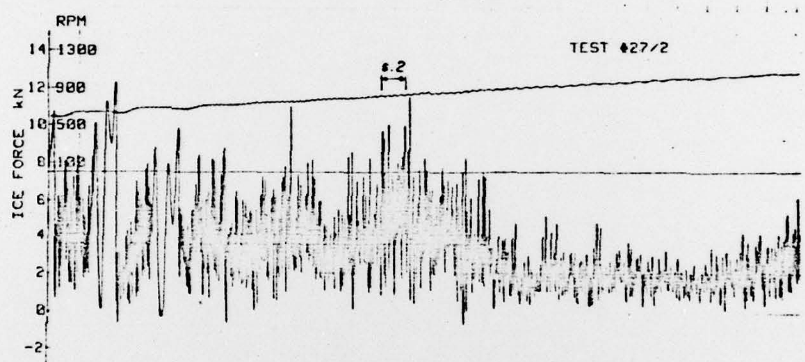


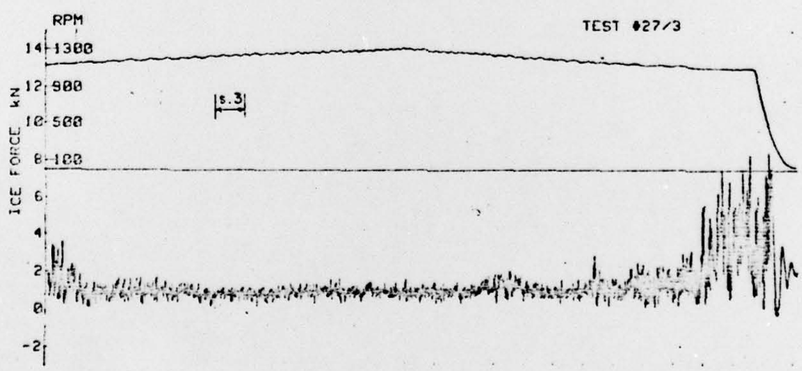
RPM
100 RPM ≅ 1.14 cm/s
Test #21/1
H = 45 mm
D = 102 mm
T ice = -1.6°C (top)
T air = -5°C
S water = 0.5%
ICE FORCE kN
SECONDS
TEST #21/2
TEST #21/3
TEST #21/4
TEST #21/5

APPENDIX 2

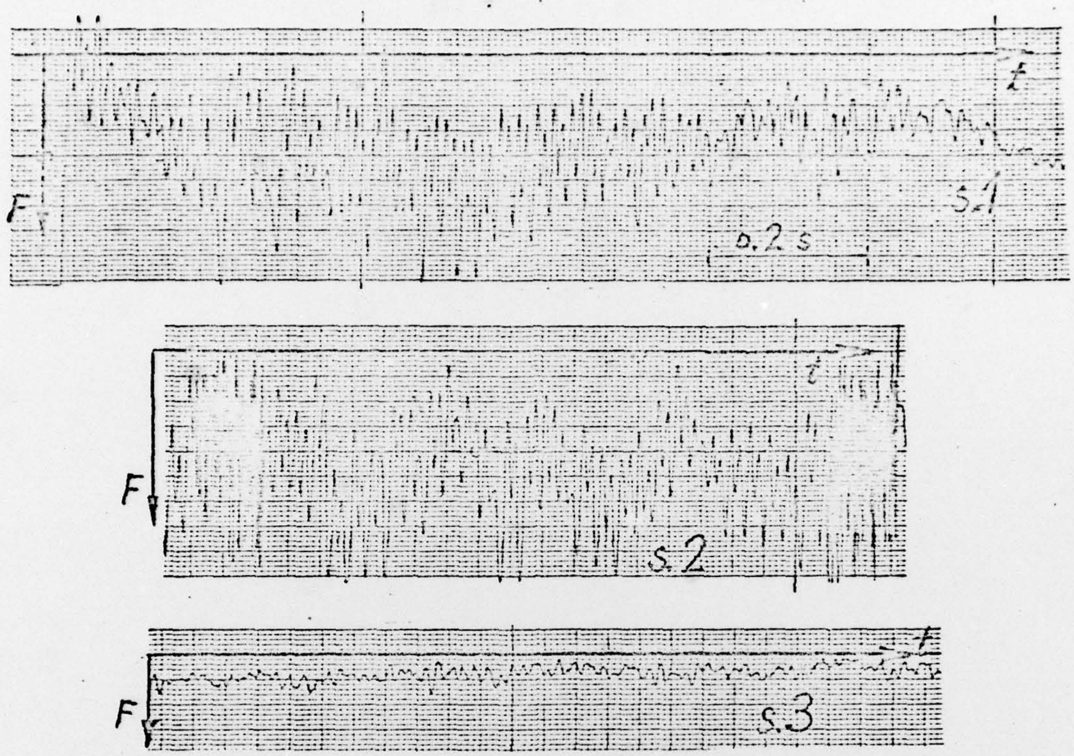
Test #27/1
H = 59 mm
D = 64 mm
T_{ice} = -0.1°C (top)
T_{air} = +2°C
S_{water} = 1.0%

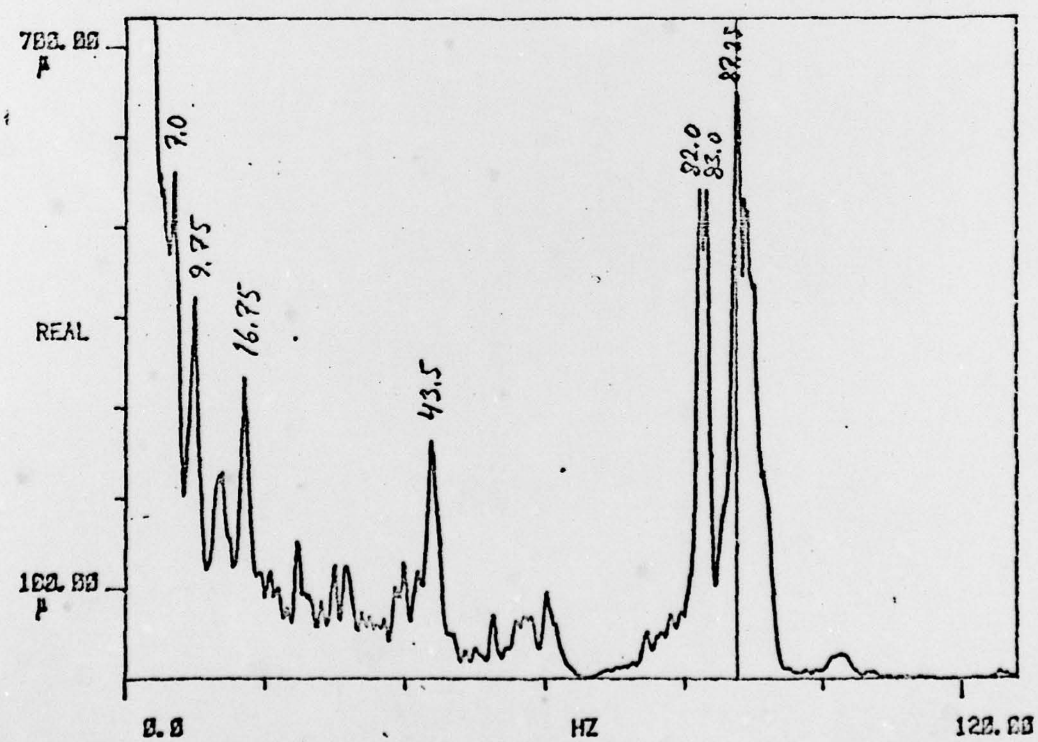






APPENDIX 3. Test # 27. Ice force samples and autospectrum





Autospectrum, from 30 to 55 seconds